Preliminary Notes on Observations made with a Horizontal Pendulum in the Antarctic Regions.

By J. MILNE, F.R.S.

Amongst the various records brought home by the ss. "Discovery" from the Antarctic Regions, a long series refer to the movements of a horizontal pendulum. This instrument, which is similar to a type adopted by the British Association and established at 38 widely separated stations in various parts of the world, was in charge of Mr. Louis Bernacchi.

When we read Mr. Bernacchi's log we recognise the exceptional difficulties, meteorological and otherwise, under which he worked. This and the fact that a hurried departure only admitted of a few hours' instruction in the practical working of the instrument he had to use, entitle him to the sincerest congratulations on the results he has brought home.

From March 14 to November 9, 1902, the instrument with its boom pointing from north to south was installed in a hut with the magnetometers. It rested on a pillar made from an earthenware drain-pipe. From November 14, 1902, to December 31, 1903, it was placed on a brick column erected in a living hut. These huts were 30 to 50 feet above sea-level at a place in longitude 166° 44′ 43″ E. and latitude 77° 50′ 50″ S., about 15 miles distant from Mounts Erebus and Terror. The former of these volcanos was always active.

The records obtained refer to Changes in the Vertical, Tremors, Pulsations, and Earthquakes. In many instances these records when taken by themselves have little value, but when analysed in conjunction with registers obtained by similar and similarly installed apparatus at very distant stations they throw light upon hitherto unsuspected phenomena which take place within and on the surface of our world.

I. *Changes in the Vertical.*

Changes in the position of the outer end of the pendulum, which is an aluminium boom three feet in length, have been measured on the seismographic films at intervals of four hours, and in certain instances every 30 minutes. These films are strips of bromide paper each 2 inches in width and 35 feet in length. They moved beneath the end of the boom at a rate of 60 mm. per hour. The total length of film brought home by

Mr. Bernacchi is about 3000 feet. One millimetre deflection of the photographic trace of the outer end of the boom is approximately equivalent to a tilt of 0·5″.

The measurement of the displacement of these traces was undertaken by my assistant, Mr. Shinobu Hirota, and Mr. Howard Burgess, of Newport, and it is in consequence of their kind assistance that the analyses of these records have reached their present stage. The results are at present in two forms—as a manuscript register and as a series of curves drawn on squared paper. Before the analysis of these records can be completed they must be supplemented with corresponding records from barographs and thermographs. The times of total darkness, continuous light, sunrise and sunset have already been entered on the squared paper. The times of sunshine and variations in atmospheric electrical conditions have not yet been obtained. Also, as Mr. Bernacchi remarks, tidal fluctuations, ice movements, changes in volcanic activity may also hold some relation to the wanderings of the pendulum. It is, therefore, desirable that information relating to these phenomena should be obtained.

A glance through the curves indicates that there have been many comparatively large and rapid deflections of the pendulum, particularly after its removal from the magnetic observatory to the living hut. For example, subsequent to the removal tiltings of 10″ have taken place in 20 hours. Displacements of this magnitude suggest a yielding of the foundations or parts of the brick column on which the instrument was installed. My own experience is, that in England it takes about 12 months for a masonry pier to become stable. A pier made with a glazed earthenware drain-pipe has only its foundation to settle and becomes stable more quickly.

There are other deviations which may be seasonal, whilst others have accompanied marked barometric fluctuations. At certain periods there have also been changes in position of the boom indicating tilts of 0·5″ to 1·0″ which have approximately a diurnal periodicity.

In " Discovery " local time the western excursion of the pendulum was most frequently completed about 11 P.M., whilst it was usually farthest east about 3 P.M., and this took place whether there was sun or no sun. To explain these changes possible distortions produced by sun heat on the earth's surface have been invoked.

That an accumulation of a water load in a valley apparently causes its two sides to approach each other, whilst a body of men approaching an observatory will cause a pendulum inside the same to swing towards the advancing load, have strengthened the suggestions that changes of level observed at a station might be influenced by differences in evaporation or of vegetable transpiration

on opposite sides of such a building.   These suggestions have each received careful attention.*

There is still another suggestion which I venture to make, and it is one which, for many reasons, I think, deserves consideration.   Briefly, this is that the observed movements are not necessarily due to tilting, but are due to electrical attractions or repulsions.   Factors to be taken into account when discussing this possibility are as follows :—

1. A small horizontal pendulum can apparently be made as sensitive as a gold-leaf electroscope, and, it may be added, might be used as an electrometer.

2. The Milne horizontal pendulum, by means of a quartz cup at the end of the boom and a silk thread at the top of the tie, is fairly well insulated, and responds to small attractive influences.

3. At Shide, the free south end of a boom which is pivoted at its north end at this season of the year (May) moves eastwards during the day and west-wards during the night.   A pendulum oriented east-west shows comparatively but little motion.

4. Movements take place when there is sunshine, even in a dark room, but with very cloudy or wet weather the movements are slight.

5. From an experiment now in progress at Shide an east-west pendulum since it has been connected to earth does not show the extensive movements it did prior to being earthed.   With the co-operation of Dr. C. G. Knott, of Edinburgh, this experiment is being supplemented with others.

II. *Tremors and Pulsations.*

As shown in the films brought home by the " Discovery," tremors usually commence as intermittent slight thickenings.   The thickenings recur at shorter and shorter intervals until there is a thickened line.   This may have a width of 0·2 mm.   The period of the movements they represent is probably near to that of the pendulum or 15 seconds.   The duration of a storm usually lies between 6 and 20 hours.   These thickenings may develop into serrations when we see that the period has been that of the pendulum.   Regular movements with amplitudes of about 0·5 mm. and periods of 60 or 120 seconds are evidently forced vibrations, and are referred to as pulsations.   These various movements have been tabulated as a register and also entered on squared paper with the curves showing changes in the vertical.   They have not yet been analysed.

III. *Earthquakes.*

Between March 14, 1902, and December 31, 1903, although there were

* See 'British Association Reports,' 1895, pp. 115 to 139, and 1896, pp. 212 to 218.

many days when the instrument was not working, 136 earthquakes were recorded. As none of these were felt by the staff of the "Discovery," it may be assumed that none of them originated within 50 miles of the station on Ross Island. A certain number were recorded all over the world, whilst many were noted at very distant observatories. These latter must have originated at distances greater than 500 miles. The measurements of the various seismograms have been drawn up as a register, which, as far as possible, contains corresponding information from 43 other stations, 38 of which have seismographs similar to that used by the "Discovery."

The results of analyses which, however, are not yet completed, point to the following conclusions :—

1. *Distribution of Origins.*—Out of the 136 records, no less than 73 refer to disturbances which originated in a sub-oceanic region lying between New Zealand and the "Discovery." A certain number of these were only recorded by the "Discovery," and the exact location of their origin is very doubtful; others were recorded at Christchurch and Wellington, others again reached Perth, while some travelled as far as their antipodes.

On the maps published annually by the British Association to indicate the positions of origin of large earthquakes, 12 districts are shown. These are named by the letters of the alphabet from A to L. Districts J, I, L are not of great importance. The extremely active locality, the existence of which has been made known by the work of the "Discovery," I propose to call District M. The high frequency in the relief of seismic strain in the latter region indicates pronounced brady-seismical movement, an inference which is quite consistent with the existence of the active Erebus and many other recent volcanic peaks. It also suggests that New Zealand may be continued towards the south-west as a sub-oceanic ridge, accelerations in the growth of which are announced by sudden yieldings along its base. The islands of Auckland, Macquarie, and others may indicate the existence of such a ridge, but I am not aware that there are any soundings to confirm the suggestion.

Sixteen records refer to shocks which originated near Japan—the Philippines and the Celebes. Five had their centres in the Himalayan region, and six off the West Coast of South America.

Seasonal Frequency of Antarctic Earthquakes.

The relative frequency of disturbances with an antarctic origin in different seasons and months for the years 1902 and 1903 is shown in the following table. The numerals in the body of the table are the index numbers of earthquakes in the "Discovery" Register :—

x 2

	Jan.	Feb.	Mar.	Apr.	May.	June.
	Seismograph only working in 1903.	Seismograph not working.	1 {3 4 5 8} 27 28	9 10 12 15 16 18 {20 21} 77 78 79 80 82	28 31 32 34 {67 68} 84 85 {86 87} 89	33 35 36 40 41 90 92 95 97 98 99
No. of earthquakes	0	—	7	13	11	11
„ distinct seismic effects	0	—	4	12	9	11

	July.	Aug.	Sept.	Oct.	Nov.	Dec.
	43 100 103 105	108 110 113 114 115	{117 118 119}	51 54 55 120 127 {128 129}	56 130 131 132 {133 134}	61 62 {63 64}
No. of earthquakes	4	5	3	7	6	4
„ distinct seismic effects	4	5	2	6	5	3

Earthquakes which are bracketed occurred within a few hours of each other, and, therefore, may possibly refer to the same relief of seismic strain. In the lower line of totals each of the groups has been regarded as a single disturbance. Whichever line we take, it seems that the greatest frequency has been in April, May, and June, or the first part of the winter months. The seasonal distribution of Antarctic earthquakes is, therefore, similar to the distribution noticed in many other countries. Dr. Omori, however, has shown that earthquakes with a sub-oceanic origin off the coast of Japan have their greatest frequency in the summer, during which season a higher average sea level more than counterbalances a diminution of load [on the sea bed, due to a lower barometric pressure. This seasonal difference in load amounts to 18·3 mm. of mercury. Whether similar conditions prevail in the antarctic regions remains to be investigated.

On the Form of Areas Disturbed by Large Earthquakes.

For local earthquakes, such, for example, as are from time to time noted in Great Britain, we are prepared to see isoseists occasionally in the form

of circles, but more frequently in the form of ellipses. The major axis of any one of these ellipses is usually parallel to the strike of a fault, the sudden yielding on the face of which gave rise to the shaking. If the movement originates at no great depth, the epifocal area where motion is most pronounced has been shown by Dr. Charles Davidson to lie on the side of the fault towards which it hades.

With very large earthquakes, which are not sufficiently strong to be recorded over the whole surface of the world, but which may reach stations near to their antipodes, the idea of elliptical isoseists requires modification.

For example, earthquakes originating in District M to the south-west of New Zealand, have been recorded to the south-east by the " Discovery," and along a band about 20° in width, extending in a north-west direction as far as Britain. They may or may not be recorded in India, whilst at comparatively near places like Batavia, Manila, and Japan, lying northwards from the origin, they have been seldom noted. Also it may be added that they have not been noted at Cape Town, or at Cordova in Argentina, each about 80° distant, nor anywhere on the American Continents. It would appear, therefore, that recordable earthquake motion originating in District M may be propagated as a band running in a north-west direction as far as its antipodes. When more stations have been established in South America, it may be found that the motion proceeds to great distances in two directions round the world. This, however, is doubtful.

Earthquakes originating off the West Coast of South America have been recorded by the " Discovery " to the south-west, but the greatest length of recognisable wave-path is found towards the north-east in which direction they have been recorded in Western Europe and also near to their antipodes in Siberia. They have not been recorded at stations we should expect them to affect were they propagated with equal intensity in an opposite direction round the world.

Disturbances with origins in Japan, the Philippines, and the East Indies have been recorded as far south as the " Discovery " and westwards across Asia and Europe, whilst they do not appear to have reached nearer stations in North America. On the westward route it may be noticed that the path would be sub-continental, whilst in going eastwards it would be sub-oceanic.

The loudness of the sound made by a gun depends in part upon the direction in which the gun is trained with regard to the observer. In a somewhat similar manner, if we hold the blade of a spade in water and then suddenly move it, the largest waves are forced in the direction of the primary impulse.

If these analogies may be used to explain why earthquakes from District M are propagated more vigorously in a north-west direction rather than in any other, one inference is that the fault or faults from which these disturbances spring strike in a north-east and south-west direction, that is, they are parallel to the New Zealand axis, and they hade towards the direction of the longest path along which movement is recorded. Similar inferences may be made with regard to the origins of movements in other districts.

Velocity Determinations.—In a few instances, when accurate data have been obtainable, calculations have been made of the speeds with which earthquake motions have been transmitted in various directions round and through the world.

Speeds along paths which are continental are being compared with those which are sub-oceanic. For example, for earthquakes with origins off the coast of Eastern Asia, the rate at which waves have been transmitted across Asia and Europe may be compared with the rate at which the same travelled beneath the Pacific Ocean to New Zealand and the "Discovery." Certain tables relating to speed strengthen the suggestion that for particular phases of earthquake motion velocity is not constant. Other tables relating to rate of propagation are only of value as indications of the character of motion which has reached distant stations.

A knowledge of the time taken by earthquake waves to travel from one seismic region to another occasionally leads to the conclusion that one earthquake may be regarded as the final cause of a second disturbance. Illustrations of earthquakes having originated in a district at the times when teleseismic movement reached that district, are to be found in earthquakes numbered 4, 8, 45, 48, and 117.

The Surviving Phase of Earthquake Motion.

With exceptionally large earthquakes we may obtain at very distant stations seismograms which exhibit all three phases of earthquake motion. More frequently, however, at such stations the record is a mere thickening of the photographic trace, a small fraction of a millimetre in amplitude, and with a duration of 3 or 4 minutes. Near to its origin the maximum motion of the same earthquake may have been pronounced, while its total duration may have extended over at least 1 hour.

The test which has been used to determine the phase of motion to which the surviving tremors represented by a thickening are to be referred has been determinations of the speed with which they have been transmitted from their origin to the station at which they were observed. In a few instances the times of origin and the positions of epifocal districts have been obtained with

a fair amount of accuracy, and the results relating to earthquake speeds may be regarded as reliable determinations of the same.

This, however, is not the case with the majority of velocity tables which have been compiled, the reason being that they have been dependent upon data relating to times of origin and positions of centres which in all probability may in certain instances deviate by 5° in distance and 5 minutes in time from the truth.

Notwithstanding this, as the velocities of P_1, P_2, P_3 for long arcs are respectively about 12, 6, and 3 kilometres per second, although the velocities deduced for surviving phases may want in accuracy, they seem to be sufficient to suggest the type of wave to which they belong. The type determined appears to be P_3, which at stations comparatively near to the origin is announced as an undulation of the earth's surface.[*]

On a Suspected Quadrantal Acceleration in Earthquake Speed.

The earthquakes here referred to are those which have been recorded at stations situated at distances of at least 90° from their origins. In well-defined seismograms these disturbances show three phases of motion. The preliminary tremors, or P_1, reach stations 60° to 180° distant from origins with average chordal velocities increasing from 11 to 12 kilometres per second. These may be compressional waves. Following these a phase P_2, which may refer to disturbance of body waves, which have over paths from 30° to 160° in length average arcual velocities increasing from 4·2 to 6·4 kilometres per second. Lastly, there is the maximum motion, or P_3, which has an approximately constant arcual velocity of 3 kilometres per second.

For the commencement of this phase, which is apparently recorded as an undulating movement of the surface of the earth, and may therefore be regarded as being partially gravitational in character,[†] the velocity becomes 3·3 kilometres per second. With regard to P_3, this, however, is a general statement. Within 10° of an origin, the value for P_3 appears to be less than 3 kilometres per second, whilst in the quadrantal region it may exceed 4 kilometres per second. These are also indicative of variation in velocity in the antipodean regions. The values for P_2 also appear to be increased in the quadrantal region. These velocity changes were first discussed in a British Association Report for 1900, p. 64 *et seq.*, but the data then at hand were not sufficient to sustain any definite conclusion.

The observations made by the " Discovery," taken in conjunction with observations referring to the same earthquakes made at other stations, have

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[*] For list of shocks showing these survivals, see ' Antipodean Recurrences,' p. 292.

[†] The influence of gravitation has been discussed by Bromwich, in ' Proc. Lond. Math. Soc.'

added to the material illustrating the phenomena here considered, and it is for this reason that I have ventured to bring the subject to the notice of the Royal Society.

Something analogous to the movement recorded on the surface of the earth is seen in Whewell's Oceanic Cotidal Chart.*   In the narrowest part of the Atlantic, between Africa and South America, the lines representing the hourly change in the position of the tidal crest are crowded together. As these travel northwards into the broader, and in places somewhat deeper, water, they are more widely separated. In other words, the tidal wave travels more quickly in the broader and deeper portions of ocean than in the narrower portions where it is retarded. Although the chart may not be "perfectly trust-worthy,"† it at least suggests that a seismic wave of the type P_3 may be less constrained, and therefore travel more quickly in its quadrantal than in its polar region. This comparison is only intended to illustrate a form of progress, and not to suggest that the factors governing the variations in speed of the tidal and seismic waves are in any way identical. Further, the seismic wave at its antipodes shows an apparent increase in its velocity, which is the reverse of that which would be expected by a tidal wave when approaching the head of an oceanic inlet.

It might be assumed that the earthquake wave passes beneath a crust and over a nucleus, into which it merges. The upper portion of such a wave would be more retarded than its lower portion. It may also be imagined that the more swiftly moving lower portion on the first 90° of its path fails to give a surface indication of its existence because its external boundaries are widening. In the quadrantal region the periphery of the boundaries are fairly constant, and it is here that we find apparent accelera-tion in its speed. Still farther on its journey excessive contraction of the boundaries results in retardation of the waves.

This is merely a suggestion for the explanation of a phenomenon the true solution of which, as Dr. C. G. Knott points out, is in all probability to be found by a consideration of effects partially due to differences in the speed of surface waves and of body waves.

Antipodean Re-appearances.

For some years past I have noticed that earthquakes which had their origin in the vicinity of New Zealand, and were recorded in that country, have also been recorded in Britain, particularly at Bidstone, but had not necessarily been recorded at intermediate stations. The "Discovery" records

* See 'The Tides,' by G. H. Darwin, p. 172.
† *Ibid.*, p. 173.

taken in conjunction with those from Christchurch, Wellington, and Perth, have confirmed this observation, and we have now a number of instances where the movement from an epifocal area has travelled round and through the world, to re-appear as a recordable quantity at its antipodes.

It is not affirmed that in the region between an epicentral district and its pole seismic movement did not reach the surface of the earth, but only that even with instruments very much more sensitive than the Milne type motion has not been detected. The phenomena under consideration might also be described as antipodean resurgences, convergences, focal effects or *contrecoups*, each of which, however, might be objected to as implying an explanation for this antipolar relationship.

In the preceding registers we find the following 19 illustrations of possible re-appearances, viz.: Numbers 1, 32, 34, 51, 53, 59, 83, 89, 91, 93, 95, 96, 108, 111, 115, 117, 120, 129, and 130.

Out of these it seems that with earthquakes numbers 1, 34, 83, 89, 95, 96, 117, 120, and 129, the surviving phase has been P_3. At Hamburg, Strassburg, and other stations where there are pendulums with a shorter period and a higher multiplication than those of the Milne type, P_1 has occasionally been recorded, *e.g.*, this is the case with numbers 1, 93, 111, and 130. In other instances the polar responses have been nearly simultaneous, a conclusion, however, which for many reasons may be more apparent than real.

The interpolar transit of a wave of the P_3 type may be compared with that of a deep-sea wave down a rapidly widening and then up a similar but rapidly narrowing estuary. The dimensions of these estuaries are assumed to be large. When half-way on its journey the height of the wave and its energy per unit area would be less than at its commencement or its terminus. It might, therefore, traverse the central area and not be noticed, but because of subsequent convergence it might become recognisable at points still further from its origin.

With very large earthquakes the movements were recorded all over the globe, and from experiments now in progress at Pribram, in Bohemia, the seismograms obtained at a depth of 1150 metres, although they show a diminished amplitude, they differ but little from those relating to the same disturbances recorded on the surface. The earthquakes we have to consider are of this type, but less in magnitude. Let us imagine one of these smaller efforts to start over an epifocal cap subtending 10° at the centre and that this expands as a ring 5° in width until it reaches the quadrantal region. The area of the cap or ring in the two positions will be approximately as 1 to 11, and if we neglect loss due to friction and assume constant energy, the intensity will be diminished in like ratio. With such conditions it seems

conceivable that a disturbance might be missed in the quadrantal region and recorded at its antipodes.   The distance to which motion would invade the superficial region between the focus and the quadrantal region would depend upon the intensity of the disturbance at its origin.

The reappearance of P_1, which is probably a condensational wave, may be accounted for by assuming that reflections are focussed in an antipodean region.

Dr. C. G. Knott, writing on this subject, says the phenomena may find its analogue in that which occurs in a whispering gallery.   Imagine an earthquake starting at a good depth, somewhat deeper than the line which separates the fairly homogeneous nucleus from the heterogeneous crust.   It is conceivable that under these circumstances the surface waves might not have time or opportunity to gather force.   The disturbances might be mostly reflected at the higher incidences, that is, at the nearer parts of the hemispherical shell. After the quadrantal regions were passed, however, the waves would impinge at more acute angles, and the surface waves would be started in sufficient strength to make themselves appreciable.   And note that, because of this very reflection at the nearer parts of the surface, there would be condensation towards the antipodal regions, there would be a greater supply of energy to draw upon in the production of the surface waves there.   The theory is in fact that under certain conditions of start the surface waves would be started late, not exactly in the neighbourhood of the earthquake, but on towards the quadrantal regions.

Seismograms, Pulsations, Magnetograms, and the Value of g.

It is now well known that at certain observatories magnetic needles are frequently disturbed by unfelt earthquake motion.   To throw light upon the consequent irregularities which from time to time are shown in the magnetograms at particular stations, horizontal pendulums have been established.   The records given by the latter instruments are due to mechanical movements, but whether the corresponding perturbations shown in the magnetograms are due to a similar cause is by no means certain.   At one station teleseismic movement may disturb surrounding and subjacent magnetic materials, with the result that needles at that station may respond to magnetic effects, which would not be the case at stations where the neighbouring materials which had been equally disturbed were non-magnetic.

At Ross Island the basalts are distinctly magnetic, while Mount Erebus and other recent cones indicate that physical and chemical characters, and also the arrangement of magnetic materials, have suffered change.

The varying activity of Erebus suggests that these hypogenic processes

have not yet ceased, and with seismic disturbances it seems probable that large bodies of magnetic magmas and rocks are at least temporarily disturbed and altered. We might, therefore, anticipate that the larger seismograms obtained by the " Discovery " would be accompanied by corresponding perturbations in the magnetograms. That a slight relationship of this description exists has already been noticed by Mr. Bernacchi, but now that the register of the " Discovery " has been extended this may be more clearly established.

When making this enquiry, large earthquakes which for various reasons were not recorded by the " Discovery " should not be overlooked. Also that the time at which disturbances of magnetic needles might be expected would probably correspond with the arrival of phase P_3 must be kept in mind.

To strengthen the assumption that " pulsations " are actual movements of the earth's surface, it would be of interest to compare the times when these were frequent with the periods when magnetic needles were unsteady or showed oscillatory movements.

The fact that the magnetic rocks on Ross Island have a high density is one reason which would lead us to expect a marked difference between the observed and calculated values for g.